Final Report

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"Tunable, Room temperature Light-emitting Diodes based on Strained Si/SiGe Heterostructures"

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Highlights

As described in the proposal, the objectives of the program are (a) to engineer SiGe/Si heterostructure for a type-I band alignment in which the emission intensity at around 1μm is enhanced over the conventional Si-based diodes, and (b) to develop light-emitting diodes based on the type-I SiGe/Si heterostructure. We have made significant progress towards achieving these objectives. As a collaborated effort between NTU, UMass Boston, and AFRL at Hanscom, USA, we have produced important results that have been published in refereed journals. This report summarizes our accomplishments and publications produced as a result of this project.

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14. ABSTRACT
This is the report of a project to engineer SiGe/Si heterostructures for a type-I band alignment in which the emission intensity at around 1 ?m is enhanced over conventional Si-based diodes, and to develop sight-emitting diodes based on the novel type-I SiGe/Si heterostructure.

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1. Accomplishment

1.1 Type-I and type-II excitons in strained Si/SiGe quantum-well structures

Si-based semiconductors are the driving force for the rapid development of revolutionary electronic technology over the past 40 years. The advance of this development, however, is expected to enter a phase of slow growth as the size of electronic devices is approaching ultimate physical and technological limits. In this project, Si-based emitters are developed based on the strained type-I structure. The designed structure is Si compatible and most importantly, the emission intensity is several order of magnitude larger than the conventional bulk materials, providing an important implication for application.

In the conventional treatment, the band profiles of Si/SiGe heterostructures with strain presented in Si (or SiGe) layer have a type II alignment where electrons and holes are localized at different layers. A schematically diagram of type-II profile is depicted in Fig 1(left,a). In this system, the optical oscillator strength (OS) is small because of the spatial separation of electron-hole wavefunctions. We have developed growth technique in this project to produce Si/SiGe quantum wells with strain distributed in both Si and SiGe layers. This allowed us to effectively manipulate the band profile for type-I structure in which both electron and hole localized at the same layers. The spatially direct type-I structure as depicted schematically in Fig 1.(left,b) has a larger OS for more efficient infrared emission. In our opinion, the proposed emission mechanism is the dominating factor for the strong emission observed in Si-based nanostructures that have been reported in the literature. With the analysis of magneto-luminescence spectra Fig.1 (right), we have shown that we can engineer band alignment of the Si/SiGe heterostructures into either type-I or type-II by manipulating the strain. By demonstrating the type-I band alignment, our investigation moves a step closer towards the realization of Si-based SiGe light emitting diodes.

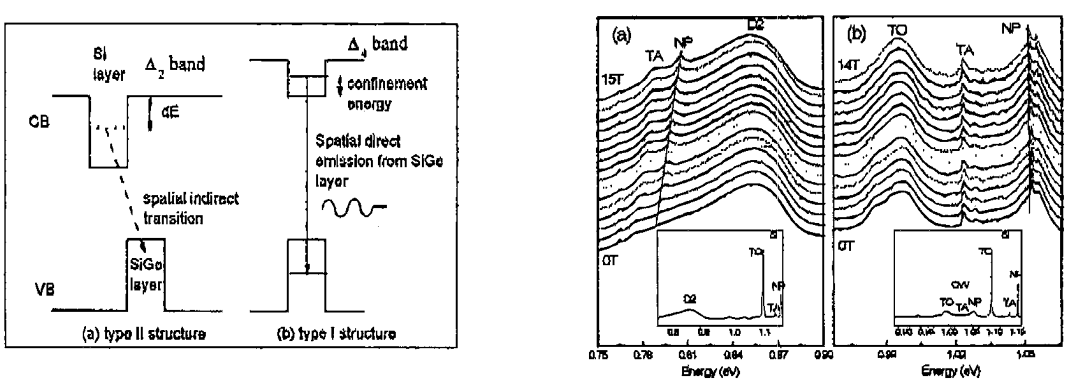

Fig. 1. (Left) Schematic diagram of: (a) Type-II band alignment of the SiGe/Si quantum well. (b)

Type-I band alignment. (Right) Magneto-luminescence spectra showing the energy shift of the no phonon line (NP) under magnetic field as marked by the solid lines for both (a) type-I and (b) type-II excitons.

1.2 Electric characteristic on type-I Si/SiGe heterostructure

On the optical measurement (photoluminescence) described above, the emission intensity is relatively weak. This is attributed to the very low carrier densities excited by the optical pumping. (Low power laser of about 10 mW is used to excite the carriers from the VB to CB. The excitation gives $\sim 10^{10}/cm^3$ carrier in the sample.) This is several orders of magnitude smaller than the typical carrier density used in the electrically pumped emission diode. For application, standard P-i-N diode structure is designed (For the diode structure, with an external applied voltage, at least $\sim 10^{18}/cm^3$ carriers are involved in the emission process.) The P-i-N diode consists of $Si_xGe_{1-x}/Si/Si_xGe_{1-x}$ double-barrier structure grown in our laboratory by Molecular Beam Epitaxy. Diode structure is fabricated and electrical characterization of current-voltage (I-V) measurement is performed. The results are shown in Fig. 2(a). The I-V curve exhibits several features as marked by the solid arrows and labeled by E1 and E2. These features correspond to the tunneling effect from the emitter through the type-I Δ band in the well to the collector. Theoretical modeling (Fig 2(b)) is also conducted based on the technique of transfer matrix method and it shows a good agreement with the data. (On the detail, see reference 4.) In combination of optical and electrical measurement, we have provided strong evidences that type-I strained Si/SiGe heterostructures can emit light with strong intensity.

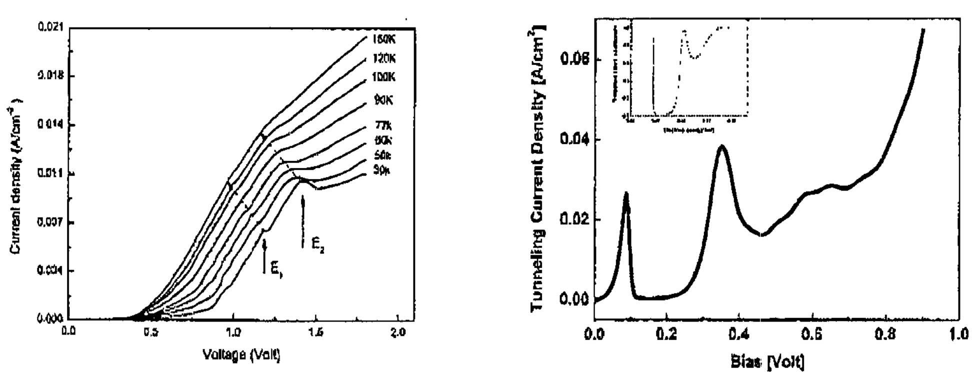

Fig. 2. (a) Left: I-V characteristics measured in the temperature range from 30 to 150 K. (b) Right: Tunneling current calculated as a function of applied bias with an insert

showing the energy-dependent transmission coefficient at the zero bias.

In the future development, we will fabricate p-i-n device structure for application.

2. Publications

(1) "Strain Free Ge/GeSiSn Qunatum cascade laser based on L-valley intersubband transitions", G. Sun, H. H. Cheng, J. Menendez, J. B. Khurgin, and R. A. Soref, Appl. Phys. Lett. **90**, 252205 (2007).

(2) "Observation of type-I and type-II excitons in strained Si/SiGe quantum-well structures", K. Y. Wang, W. P. Huang, H. H. Cheng, G. Sun, R. A. Soref , R. J. Nicholas, and Y. W. Suen, Appl. Phys. Lett. **91**, 072108 (2007).

(3) "The characteristic of strain relaxation on SiGe virtual substrate with thermal annealing", W. P. Huang, H. H. Cheng, G. Sun, R. F. Lou, J. H. Yeh, and T. M. Shen, Appl. Phys. Lett. **91**, 142012 (2007).

(4) Electron tunneling in a strained n-type $Si_{1-x}Ge_x/Si/Si_{1-x}Ge_x$ double-barrier structure, K. M. Hung, T. H. Cheng, W. P. Huang, K. Y. Wang, H. H. Cheng, G. Sun, and R. A. Soref, Appl. Phys. Lett. **93**, 123509 (2008).